Agricultural Water Management 204 (2018) 17–27

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Hydro-power energy recovery in pressurized irrigation networks: A case study of an Irrigation District in the South of Spain

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ARTICLE INFO

Keywords:
Hydropower
Energy recovery
Irrigation network
Turbines
PAT

ABSTRACT

As a result of climate change, higher irrigation water demands are predicted in the future in pressurized irrigation networks. This will result in larger energy requirements and greater CO_2 emissions levels for irrigation networks powered by pumping systems. Therefore, measures to counteract this growth in energy and CO_2 emissions in the agri-food sector, such as energy recovery using hydropower, are becoming imperative.

The Bembézar Margen Izquierda (BMI) Irrigation District, in Southern Spain, has been analysed and simulated for several water demand scenarios using a model based on the hydraulic simulator EPANET. Results show that a substantial amount of energy used for the distribution of irrigation water can be recovered. Flows and heads available at four different locations in the network showed suitability for the installation of one traditional Francis turbine and three Pumps-as-turbines (PAT).

The methodology used was divided into four phases. In the first phase, the network was simulated with all hydrants simultaneously open and the best locations to install HPP (Hydro Power Plant) were assessed. In the second phase, the maximum, minimum and mean flows and available head values per month at each HPP location were obtained using on-demand simulations applying the Clément methodology. In the third phase, the flow and net head available in the turbines were transformed into energy. In the last phase a feasibility study was carried out through three indices. Applying this methodology, the maximum recoverable energy was estimated as 270.5 MW h and the maximum carbon savings potential was estimated as 108 t eCO_2. These technologies represent a positive competitive advantage for agricultural production reducing the carbon footprint and therefore improving the sustainability of the agricultural production.

1. Introduction

In pressurized water distribution systems, the dissipation of energy to avoid excess pressure is typically conducted using Pressure Reducing Valves (PRV) or break pressure tanks. The fitting of a turbine in a pipe network, instead of a PRV, is an attractive alternative to reducing excess pressure while also generating electricity, evidenced since the late 1980's (Penche, C., 1998). Recently, the concept of energy recovery using micro-hydropower has been studied in much more detail by many different authors, and primarily in the drinking water supply setting (Ramos and Borga, 1999; Gaius-obaseki, 2010; McNabola et al., 2011; Carravetta et al., 2012; Lydon et al., 2017a).

The energy savings potential at an individual excess pressure site is typically small (2–20 kW). However, many traditional turbine technologies cannot be miniaturized to such capacities without prohibitive costs. This drawback has been solved partially with an innovative technology named Pump-As-Turbine (PAT). The fundamentals of PAT theory are well established in Carravetta et al. (2018). PATs are pumps operating in reverse to produce energy instead of consume it (Ramos and Borga, 1999; Carravetta et al., 2012; Fecarotta et al., 2015). This is a well-known concept in the water industry and is an efficient method of generating power as well as recovering energy while contributing to savings (McNabola et al., 2014).

Although the peak performance of a PAT is typically less than that of a conventional turbine, the cost can be up to 10–20 times less (Power et al., 2016). From the economical point of view, it is often stated that the capital payback period of PATs in the range of 5–500 kW is two years or less (Derakshan and Nourbakhsh, 2007; Carravetta et al., 2013). Other authors have estimated this value between 2.5 and 6 years (Marchis et al., 2014), and 4.7 years in a recent study (Lydon et al., 2017a). The large differences in cost reported in literature are due to the influence of civil works, piping, and/or electronics, as well as economies of scale. The use of conventional turbines in a micro-hydropower (MHP) setting typically yields a payback of 8–10 years in

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https://doi.org/10.1016/j.agwat.2018.03.035
Received 13 December 2017; Received in revised form 19 February 2018; Accepted 24 March 2018
Available online 05 April 2018
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economically viable cases (Corcoran et al., 2013). All these works have focused on urban water supply networks and not on the irrigation sector, which usually has higher fluctuations in water demand, as well as different seasonal and daily demand patterns.

A turbine is often designed to operate at a relatively fixed flow rate and head which correspond to its maximum efficiency. As flow or pressure change from this best efficiency point (BEP), the performance of the system is reduced. This results in less energy being generated and can increase significantly the payback period of the installation. Nevertheless, most conventional turbines have low sensitivity to changes in flow rates. Variations of ± 50% will not imply significant drops efficiency. However, the range of flow rates over which a single PAT can operate is usually much narrower than in a conventional turbine and it should be carefully selected to obtain the best possible efficiency (Fontana et al., 2012). The efficiency of a PAT drops abruptly with small flow variations. Previous research in drinking water supply networks has shown that when the flow deviates +20% from the BEP, the performance is reduced by up to 22%. When the deviation is −20% the performance reduction drops by 70%. This aspect highlights the need for PAT operation to be controlled close to the BEP (Lydon et al., 2017a). Flow fluctuations of this magnitude (20%) are commonly found in irrigation networks. Preliminary studies were carried out considering the annual average flows (Estrada and Ramos, 2015). Other researchers analyzed in more detail the flow variations and calculated the maximum theoretical energy recovery coming from the energy dissipated in the network because of friction losses (Pérez-Sánchez et al., 2016).

Energy recovery in irrigation has significant relevance to the sector since many farmers cannot apply the full crop water needs due to the high cost of the energy. This high cost forces farmers to concentrate the irrigation when the cost of the energy is lower. Previous investigations have shown that high energy requirements have led farmers to apply less water than the maximum theoretical irrigation needs, thus applying deficit irrigation as a strategy to maximize profits versus the traditional maximization of crop yield (Rodríguez Díaz et al., 2011). Under this scenario, methodologies to reduce the energy consumption are critical such as: irrigation network sectoring (Fernández García et al., 2013), critical hydrant detection (Rodríguez-Díaz et al., 2012), irrigation scheduling in turns (Moreno et al., 2010), solar pumping (Mérida García et al., 2018) or the use of variable speed drives (Fernández García et al., 2013). But once these measures are undertaken, the recovery of the energy inherent in excess pressure in the network should be investigated. Hydropower energy recovery in irrigation is still largely unexplored and requires further investigation. All these methodologies should be considered as useful tools for both, the reduction of energy consumption and the recovery of the excess energy in pressurized irrigation networks. This energy generation could contribute to reducing the exploitation costs of these systems, increasing the competitiveness of agricultural production and reducing the carbon footprint of irrigated crops.

The scope of this work was to quantify the potential of hydropower energy recovery in a pressurized irrigation network, assessing its technical and economic feasibility. The maximum flow circulating in the network and available head were estimated using statistical methods and computer simulations. Pressure regulator valves (PRVs) were used to represent the head-loss that would be induced by a turbine placed in the network to reduce pressure and recover energy. The economic analysis was conducted in terms of Power (kW), Energy recovery (kW h) and potential revenues of recovered energy (€), as well as its economic viability through the payback period, the power index (€/kW) and the energy index (€/kW h). The analysis was applied to a real case study during one irrigation season (2014–2015) in Southern Spain.

2. Material and methods

2.1. Study area

The left bank of the Bembézar river irrigation district (BMI) is in the Guadalquivir River Basin (GRB), near to the city of Córdoba (Andalusia, Southern Spain). Average annual rainfall in BMI was slightly higher than 500 mm and potential evapotranspiration was around 1400 mm (Rodríguez Díaz et al., 2007b). The main crops in BMI (4000 ha) are Citrus (47%), Maize (26%), Olive trees (10%), and Sunflower (3%) (Fernández García et al., 2014a).

BMI is characterized by a steep topography with hydrant elevations ranging from 58 m to 103 m (Fig. 2a). This branched irrigation network is comprised of 28 hydrants designed to supply 1.2 $Ls^{-1} ha^{-1}$ with a service pressure of 35 m. Water is conveyed through 220 pipes with a total length of 32 km. Currently the irrigation network is operated on-demand, which means that water is continuously available to farmers. This network is an interesting candidate to assess hydropower energy recovery potential, due to the difference in elevation within the system.

The pumping station (elevation of 93 masl) was originally designed to supply water on-demand and is composed of seven split case horizontal centrifugal pumps. There are 2 types of pumps: A, with lower power to supply water when a few hydrants are open, and B, higher power pumps. There are three pumps of type A (315 kW) and four of type B (800 kW). One of the 315 kW pumps is activated with a variable speed pump (VSP), and the others operate as fixed speed pumps. The sequence of activation is the variable speed pump (VSP) followed by all A and B pumps, consecutively.

2.2. Methodology

The methodology was divided in four phases. A schematic representation of the methodology is shown in Fig. 1. In the first phase, the network was simulated with all hydrants simultaneously open and the best locations to install HPP were assessed. In the second phase, the maximum, minimum and mean flows and available head values per month at each turbine location were obtained using 3000 on-demand simulations applying the Clément methodology (Clément, 1966). This methodology simulated a more realistic scenario than in phase 1, where multiple combinations of open and shut hydrants were simulated across the network, yielding a distribution of flow variations based on flow probabilities. In the third phase, the PAT/turbine sizing was performed according to the flow rates and excess pressure calculated in the HPP locations after the computer simulations. In the last phase a feasibility study was carried out through three indices, the payback period, and the power and energy index.

2.2.1. HPPs locations

The hydraulic simulator EPANET (Rossman, 2000) was used to select the best locations to install the hydropower plants (HPPs). The excess pressures were detected after a simulation considering that all the hydrants were simultaneously open (most unfavorable conditions, which would rarely occur in practice). The locations with the largest excess pressure were selected, starting from the pump station (higher flows). In these locations, pressure reduction valves (PRV) were modeled and set at the value that ensured a minimum pressure of 35 m in the most critical hydrant downstream (Fig. 2b). PRVs were used to represent the head-loss which would be induced by a turbine placed in the network to reduce pressure and recover energy. The same procedure was used in the different branches of the irrigation scheme to calculate the excess pressure within the network without compromising the service pressure in the most critical hydrants.

2.2.2. On-demand simulations

In the previous phase the best locations were selected considering that all hydrants were simultaneously open. However, in on-demand

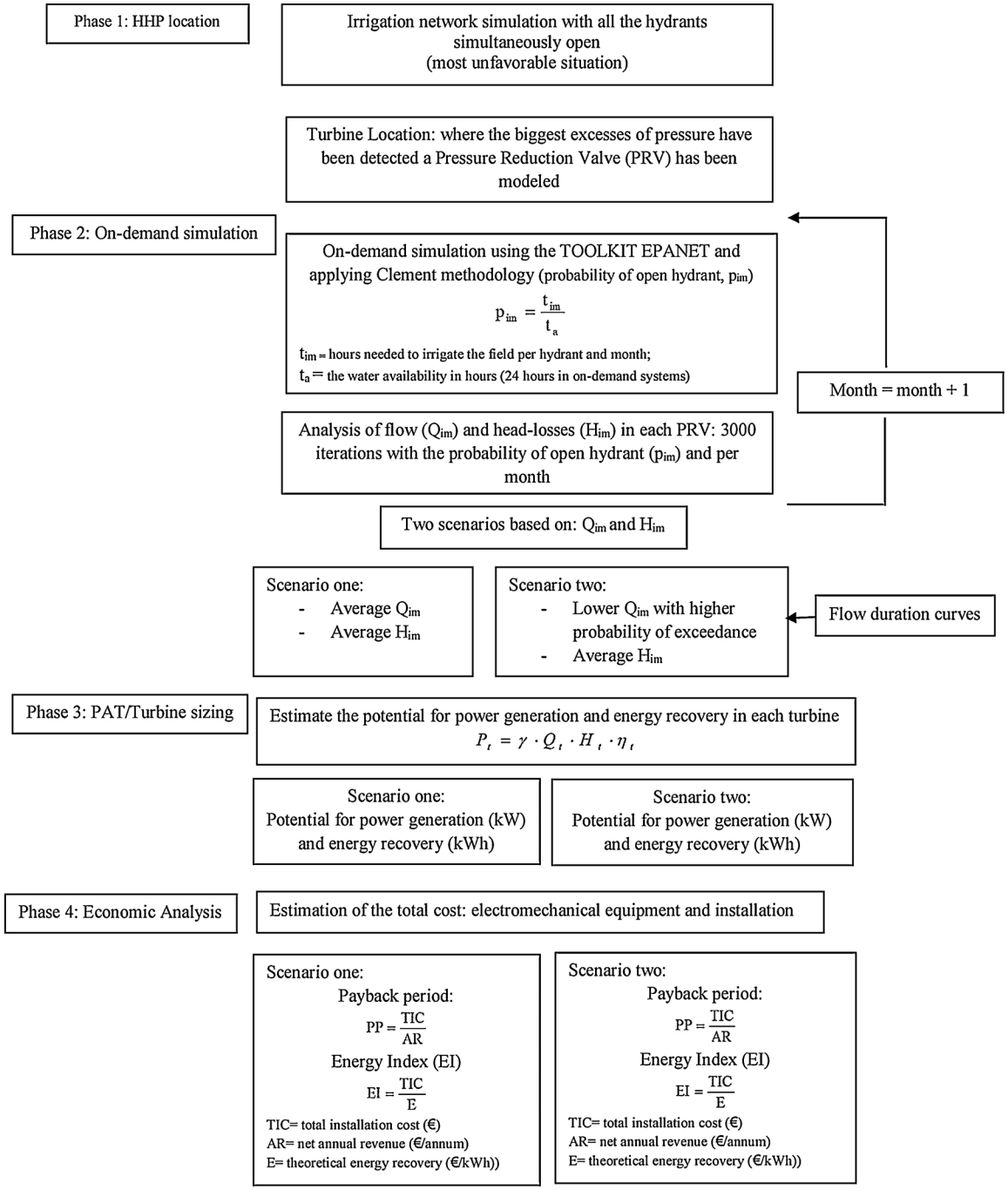
Phase 1: HHP location
Irrigation network simulation with all the hydrants simultaneously open (most unfavorable situation)
Turbine Location: where the biggest excesses of pressure have been detected a Pressure Reduction Valve (PRV) has been modeled
Phase 2: On-demand simulation
On-demand simulation using the TOOLKIT EPANET and applying Clement methodology (probability of open hydrant, pim)
$p_{im} = \frac{t_{im}}{t_a}$
tim = hours needed to irrigate the field per hydrant and month;
ta = the water availability in hours (24 hours in on-demand systems)
Month = month + 1
Analysis of flow (Qim) and head-losses (Him) in each PRV: 3000 iterations with the probability of open hydrant (pim) and per month
Two scenarios based on: Qim and Him
Scenario one:
- Average Qim
- Average Him
Scenario two:
- Lower Qim with higher probability of exceedance
- Average Him
Flow duration curves
Phase 3: PAT/Turbine sizing
Estimate the potential for power generation and energy recovery in each turbine
$P_t = \gamma \cdot Q_t \cdot H_t \cdot \eta_t$
Scenario one: Potential for power generation (kW) and energy recovery (kWh)
Scenario two: Potential for power generation (kW) and energy recovery (kWh)
Phase 4: Economic Analysis
Estimation of the total cost: electromechanical equipment and installation
Scenario one:
Payback period:
$PP = \frac{TIC}{AR}$
Energy Index (EI)
$EI = \frac{TIC}{E}$
TIC= total installation cost (€)
AR= net annual revenue (€/annum)
E= theoretical energy recovery (€/kWh))
Scenario two:
Payback period:
$PP = \frac{TIC}{AR}$
Energy Index (EI)
$EI = \frac{TIC}{E}$
TIC= total installation cost (€)
AR= net annual revenue (€/annum)
E= theoretical energy recovery (€/kWh))

Fig. 1. Schematic representation of the methodology.

networks the flows throughout the day are not constant and depend on the number of hydrants that are irrigating at the same time, implying that water demand tends to be concentrated in certain hours of the day (Pereira, 1999; Lamaddalena and Sagardoy, 2000; Rodríguez Díaz et al., 2007a, 2009). To take this effect into account, Clément suggested that two possible states may be considered for each hydrant: the outlet is open with a probability, *p*, or the outlet is shut, with a probability, *1-p* (Clément, 1966; Lamaddalena and Sagardoy, 2000). The probability of an open hydrant (p_{im}) was estimated as the quotient between daily hours needed to irrigate the field associated to each hydrant and month (t_{im}) and the water availability time in hours (t_a) per day. In on-demand irrigation systems the water availability (t_a) is 24 h.

$$p_{im} = \frac{t_{im}}{t_a} \quad (1)$$

The irrigation time required in hours, per hydrant and month, t_{im} was calculated as follows:

$$t_{im} = \frac{1}{3600} \cdot \frac{IN_{im}}{q_{max}} \quad (2)$$

Initially the existing crops associated with each hydrant during the irrigation season were recorded. From these data, the theoretical daily average irrigation needs per month and hydrant (mm) were estimated as described in FAO 56 (Allen et al., 1998). This was conducted using the computer model CROPWAT and climate data collected in a local agro-climatic station. This information in mm can be easily transformed into irrigation needs, IN_{im} in (l/ha/day). On the other hand, q_{max} was the design flow allowed per unit of irrigated area, equal to 1.2 l/s/ha for this network. The result of t_{im} is in seconds and the conversion constant

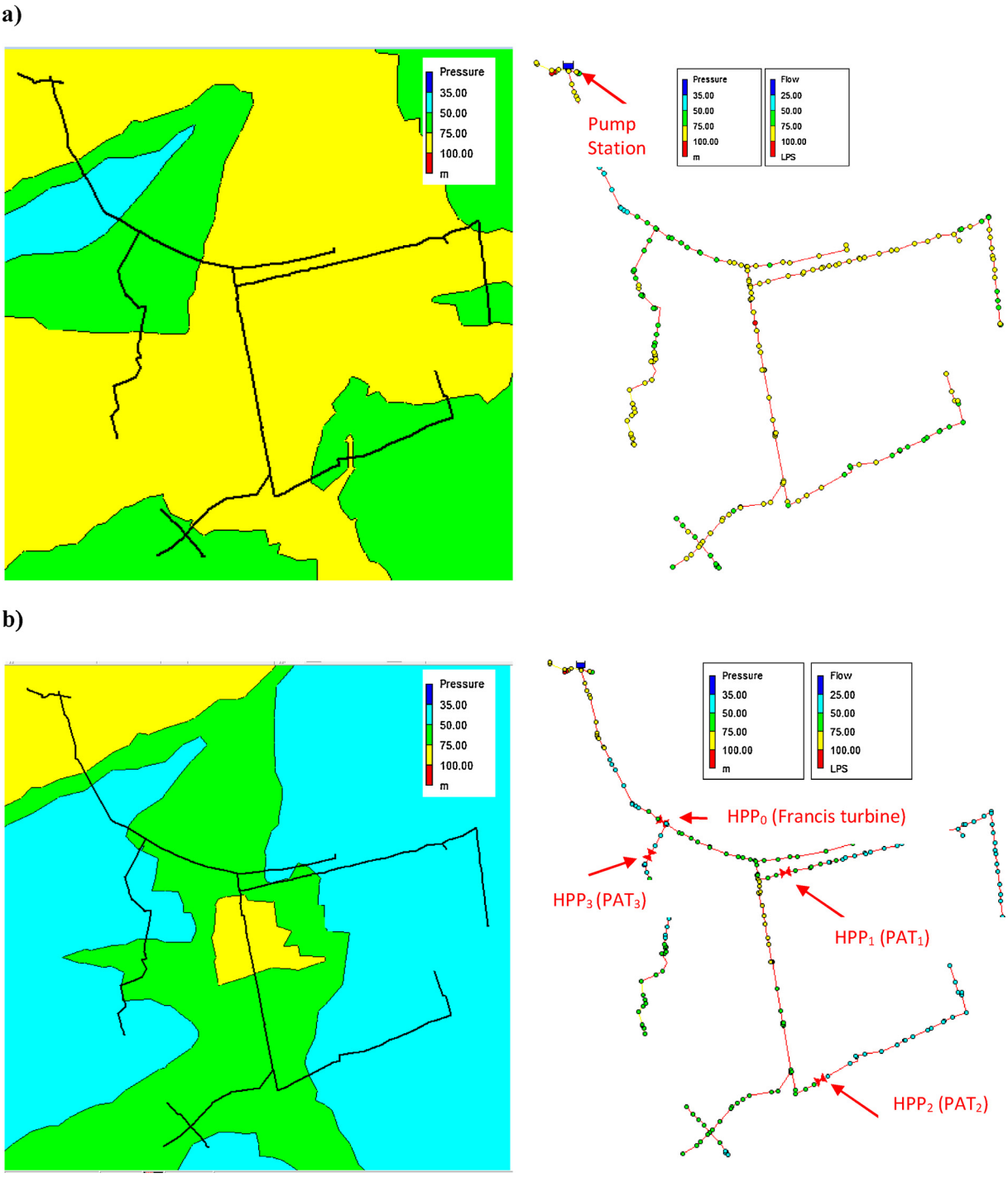

Fig. 2. Pressure contour plot and layout of the BMI irrigation network initially (a) and after the Hydro Power Plants (HPP_s) construction (b).

3600, is to transform the units into hours.

The Clément's open hydrant probability was incorporated into the model according to the methodology suggested by Carrillo-Cobo et al. (2011). This methodology included an algorithm that established random demand patterns of open and closed hydrants for every month depending on the theoretical irrigation needs (IN_{im}) and the open outlet probability (p_{im}). The model analyzed the behaviours of the network for a wide range of probabilities. Sets of operating hydrants were defined by assuming a uniform distribution across the hydrant and generating random numbers R; if R was less than or equal to *p* the hydrant was assumed open. If not, the hydrant was assumed closed and its base demand was set to zero. With this variability in open hydrants, a wide range of daily flows were included in these simulations.

The EPANET engine was integrated into an external program (MATLAB, vR2012b) through its Dynamic Link Library (DLL). 3000 iterations of the probability of open hydrant have been simulated each month during the irrigation season. Maximum, minimum and average daily flows and available head per month in each PRV were simulated through this process.

2.2.3. PATs/Turbines sizing

Sizing PATs or turbines to recover energy in the irrigation network setting required a balance to be struck in design terms between the variable performance of these devices (varying power output with

varying flow and pressure input) and the very fluctuating nature of flow and pressure in on-demand irrigation networks. Firstly, the PATs/turbines were designed in the HPPs points. Hereafter, two flow scenarios were selected taking into account the probability of flow exceedance. Finally, the efficiency of the machine was fixed considering the installation of a by-pass ensuring that the turbine worked most of the time near to its BEP.

2.2.3.1. Turbine type. PAT or traditional turbines were selected for each network location depending on the hydraulic conditions of flow and pressure. For power outputs over 100 kW the Francis turbine was considered, and below this value PATs were selected (Ramos et al., 2009).

The head-losses and flows obtained in each PRV after the simulations were transformed into energy (power in kW) according to Eq. (3).

$$P_{H_{tm}} = (\gamma \cdot Q_{tm} \cdot H_{tm} \cdot \eta_{tm})/1000 \quad (3)$$

Where *t* (from 1 to 4) is each turbine or PAT installed in the irrigation networks, γ is the specific weight fluid (9810 N/m^3), Q_{tm} is the average flow in each turbine per month (m^3/s), H_{tm} is calculated as the average head-loss registered in each PRV per month (head in the node upstream minus pressure to which the PRV is fixed) and η_{tm} is the hydraulic performance in each turbine in each month.

2.2.3.2. Modeling scenarios considering the probability of flow exceedance. As a result of their characteristic behaviour, PATs cannot be designed for the maximum flow rate since the equipment would be oversized, working most of the time with lower flows and therefore producing low efficiency values. The flow duration curves per month show the exceedance probability (%) for a certain flow rate. Based on these flow duration curves, PATs should be designed for average flows encouraging higher efficiencies for the longest period of time. In addition, the design flow value should have a high probability of exceedance during the months that comprise the irrigation season. If the average flow in these months does not have sufficiently high flow exceedance, then lower flow values must be considered to increase the efficiency of the turbine.

The flows were monitored in all the pipes where the PRVs were simulated. For the purposes of selecting a design flow at each PRV, two scenarios were considered:

a) The first scenario considered the mean flow value registered during the irrigation season, from April to September. Thus, higher flows were expected only during the peak irrigation season. But which is the exceedance probability of this flow in each month during the irrigation season? This can be addressed with flow duration curves. If the probability is low, then most of the time the targeted flow is not achieved. Therefore, another scenario was considered.
b) In the second scenario a lower value than the average flow was used. The aim was to obtain the maximum values of flow exceedance during a longest period of time during the irrigation season. Although there is a lower potential for power generation, there is a higher probability of flow exceedance in this scenario.

2.2.3.3. PAT/Turbine efficiency and power generation. The efficiency of a PAT drops off abruptly with small flow variations below and above the (BEP) best efficiency point (Lydon et al., 2017a). Under such conditions, a by-pass and a flow control regulator valve must be implemented in the system to ensure that the PAT works most of the time near to the BEP. The installation scheme of the PATs is shown in Fig. 3 as it is described by several authors (Carravetta et al., 2012; Lydon et al., 2017a).

The bypass system assures the achievement of the following rules:

$$\text{If } Q < Q_d \text{ then } q_1 = 0 \text{ and } q_2 = Q; \quad (4)$$

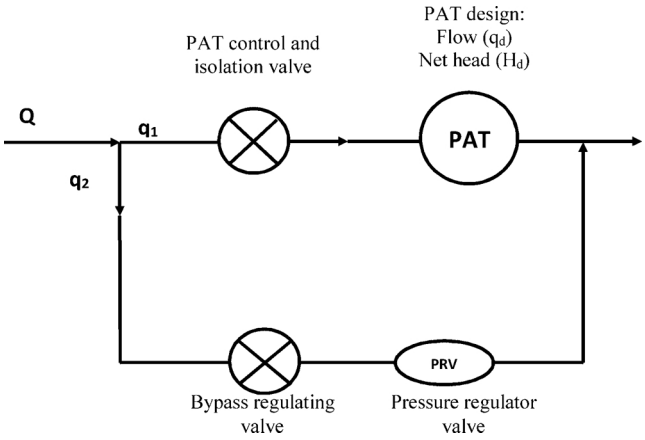

Fig. 3. Installation scheme of a PAT.

$$\text{If } Q > Q_d \text{ then } q_1 = Q_d \text{ and } q_2 = Q - Q_d \quad (5)$$

where Q is the pipe flow (m^3/s), Q_d is the PAT design flow rate (m^3/s), q_1 is the flow diverted to the PAT (m^3/s), and q_2 is the flow diverted to the bypass system.

The global efficiency for PATs installation was considered as 0.5 (0.65 PATs efficiency plus generator, 0.95 for the transformer and 0.85 the hydraulic regulation).

PATs have no ability to regulate flow rate or pressure by themselves unlike most conventional turbines. The lack of a regulation device means that regulation must be achieved externally (hydraulic regulation) and some flow must be diverted to maintain the backpressure and to operate the PAT close to its best efficiency point.

In contrast, good efficiency in the Francis turbine is maintained across significant deviations from its BEP. This means that good performance is maintained for considerable drops from the nominal flow (40–50%). Also, it has good performance for flows above the design flow (+10%). The maximum efficiency value for a Francis turbine is approximately 85–90% and drops to 75% for a reduction in the flow of about 50% (Castro, 2006; BHA, 2012). For this study, the global plant efficiency for traditional turbines has been estimated as 0.6 (turbine efficiency 0.87, generator efficiency 0.85, transformer efficiency 0.95, and hydraulic regulation 0.85).

Once the type, flow design and performance of the different machines were selected the power generation of each one was calculated according to Eq. (3).

2.2.4. Economic analysis

2.2.4.1. Feasibility study. The feasibility of these installations is linked to their economic viability. For this analysis the payback period (PP) and energy index (EI) have been used as indicators of investment viability (Pérez-Sánchez et al., 2016; Lydon et al., 2017b; Castro, 2006). PP and EI are defined in Eqs. (6) and (7):

$$PP = \frac{TIC}{AR} \quad (6)$$

where: PP is payback period (years), TIC is the total installation cost (€) plus the annual maintenance and operation cost (3% of TIC) and AR is the net annual revenue (€/annum).

$$EI = \frac{TIC}{E} \quad (7)$$

where: EI is the energy index (€/kW h or €/kW), and E is the theoretical energy recoverable by the turbine or PAT (kW h/year or kW/year).

2.2.4.2. Installation cost (TIC). Carravetta et al. (2013) estimated PAT unit costs of €230–350 per kW, considering only the electro-mechanical equipment. Also, Ramos et al. (2009) estimated the initial investment

for a unit of power between €250 and €400 for power outputs up to 40 kW. In this study a unit cost of €350 per kW was selected for the PAT cost estimation, only for the electro-mechanical equipment. The cost of the total installation followed in this research was defined by Lydon et al. (2017b). The PAT and generator were the dominant cost factor accounting for 65% of the installation cost. The civil works (ground works, manhole and foundations) represented 25% of the cost. The remaining 10% was associated with pipe works, fittings and valves.

In the case of Francis turbines, Ogayar and Vidal (2008) formulated Equation (8) (€/kW), as a function of the power (P, in kW) and net head (H, in meters):

$$\text{Cost} = 25698 \cdot P^{-0.560135} \cdot H^{-0.127243} \quad (8)$$

The total cost of the installation also includes the civil works and pipe works among others. Also, a maintenance and operation cost of 3% of the total cost has been considered. Additional infrastructures required for the use of the recovered energy have not been considered in this study.

2.2.5. Methodological limitations

The proposed methodology has limitations. In irrigation networks, flow rate variations occur across the long and short term. Long term changes in flow rate can be influenced by climate change, policy factors such as water pricing or land use planning, changes in the European agricultural policy, or the market prices of agricultural products. Short term changes arise from irrigation demand patterns which depend on many factors such as: inter and intra-annual crop rotation, climatic data, fertigation programs, chemical treatments, among many others. In addition, the current energy price has promoted a crop conversion towards more profitable crops which demand higher amounts of water. Farmer's behaviour tends to adapt to this situation displacing the irrigation when the price of the energy is cheaper. Thus, many factors may influence the irrigation demand over time and only one irrigation season has been modeled in this work.

Since the measurements of the flow are not possible in each pipe, the Clément methodology has been applied. This method has been widely used in the design of irrigation networks and to simulate energy saving scenarios under different approaches such as sectoring and critical point detection, optimal operation of the pressurized network, or the energy cost optimization (Lamaddalena and Sagardoy, 2000, Rodríguez Díaz et al., 2009; Fernández García et al., 2014b).

3. Results

The methodology has been applied to the BMI irrigation network during the 2014–2015 season.

3.1. Hydro power plants (HPPs) location

Four different locations for HPPs installation have been detected within the irrigation network (Fig. 2b). The PATs/Turbines installed in the HPPs were designed to ensure a minimum of 35 m in the most critical hydrants downstream.

3.2. On-demand simulation

During the irrigation season, from April to September, the water demand was very high, increasing from April until July and decreasing subsequently until September. Average flows and excess pressures obtained after 3000 simulations for each turbine across each month are summarized in Fig. 4. The flow for the Francis turbine was much higher than for the three PATs, with maximum values in June and July of 1.7 m^3/s. For the PATs these values were lower with values in June and July between 0.17 and 0.43 m^3/s. On the other hand, the pressure excess was quite constant for each location over the year. During the more demanding months, the increase of the flow demanded implied higher values of head-losses and therefore a decrease of available head for power generation.

3.3. PATs/Turbine sizing

3.3.1. Turbine type

For HPP_0 the average flow rate during the irrigation season was 1.25 m^3/s with a maximum value of 1.75 m^3/s in June and a minimum value of 0.66 m^3/s in September. The excess of pressure was 26.8 m. In this case, the equipment that best matched the flow and available head at this particular location was a Francis turbine.

For the remaining HPPs, the average flow ranged between 0.13 and 0.31 m^3/s. The average values of pressure excess for HPP_1 and HPP_2 were 27.2 and 29.2 m respectively, while in HPP_3 was 12.8 m. Thus, for these three locations a PAT system was recommended PAT_1, PAT_2, and PAT_3 respectively.

In Fig. 4 the average daily flow values per month were shown, but it should be noted that these values are the average of 3000 simulations per month. Fig. 5 shows the variation of flow versus available head for the 3000 simulations for the Francis turbine in July and April. In July the minimum flow of the simulations was close to 0.5 m^3/s and the maximum was over 3 m^3/s. The average value was 1.7 m^3/s. The analysis was similar for the available head, with variation from 23 to 28 m for the entire simulations.

3.3.2. Modelling scenarios considering the probability of flow exceedance

For the HPP_0 location, considering the average flow during the irrigation season of 1.25 m^3/s (first scenario), the probability of exceedance was 60% during May and August, and 85% in June and July (i.e. there was a 60% likelihood in May and August that the daily flow in the network exceeded this average value). In April and September the flow exceedance was very low, under 10% (see Fig. 6). Moreover, in these two months the typical flow dropped to almost 50% of the average and therefore the efficiency of the turbine would be very low and has not been considered for power generation.

The design flow fixed for the second scenario was 1 m^3/s. The exceedance probability was higher than in scenario one, with values around 85% in May and August, and 95% in June and July. The flow was reduced in April and September by 23.2 and 32.6% respectively. Although power could be generated with this flow reduction for a traditional turbine, the exceedance probability was very low (10–20%) and therefore these months have not been considered for power generation. The same analysis was carried out for the PATs.

3.3.3. Turbine efficiency and power generation

Fig. 7 shows the potential for power generation (kW) and energy recovery (kW h) for both scenarios. For scenario one, the power generated by the Francis turbine (HPP_0) comes to 191.3 kW. For scenario two, the potential power generated was 153.0 kW from May to August. The total energy recovered considering the irrigation time required to satisfy crop water requirements summed up to 197.9 MW h and 158.3 MW h respectively.

Fig. 7 also shows the power generated and recoverable energy for the three PATs installed in remaining three HPPs locations and for both scenarios. For PAT_1, the power generated for both scenarios were 39.7 and 26.5 kW respectively. Considering the irrigation time required to satisfy crop water needs, the energy recovered amounted to 41.1 and 27.4 MW h respectively. For PAT_2 these figures were 22.8 and 14.2 kW for power generation and 23.5 and 14.7 MW h for energy recovery. Finally, for PAT_3, the potential for power generation was 7.7 and 4.7 kW and the potential for energy recovery was 7.9 and 4.9 MW h.

The total power generated by the Francis turbine and three PATs came to 261.4 and 198.4 kW for both scenarios and the total energy recovered values amounted to 270.5 and 205.3 MW h respectively. 73% of recovered energy came from the Francis turbines, 15% from PAT_1, 9% from PAT_2, and 3% from PAT_3.

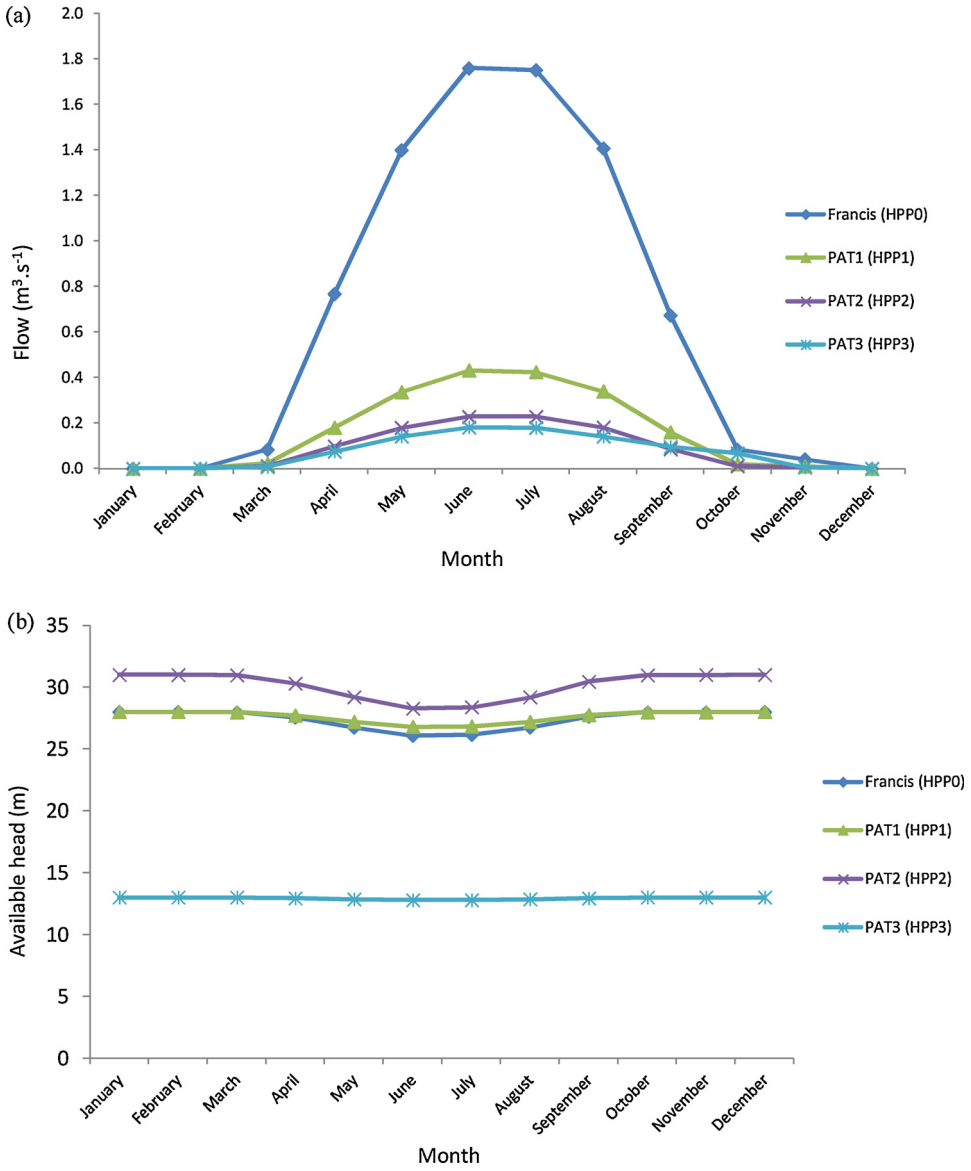

Fig. 4. Average flows and available head in each Turbine/PAT after 3000 iterations during the irrigation season (Apr–Sep).

3.4. Economic viability

3.4.1. Total cost

3.4.1.1. Francis turbine. Table 1 shows the HPPs total cost for both scenarios. The cost of the electro-mechanical equipment was €171198 and €155175.5 for 191.3 and 153 kW of power respectively, and 26 m of available head. Considering pipe works, fittings and valves (10%) and the cost of the civil works (25%), the total cost of the installation was €263382.6 and €238731.5 respectively. These values were increased with the maintenance and operation cost of 3%.

3.4.1.2. PATs. The total cost of the PATs installations is shown in Table 1. PAT_1 plus the generator had a cost of €13707 and €9138 for scenarios 1 and 2 respectively. The total cost considering pipe works and civil works was €21088 and €14058. On the other hand, PAT_3, the smaller one had a total cost of €4061 and €2499 respectively. Total cost of PAT_2 was between the other two, €12079 and €7550.

3.4.2. Installation revenues

Revenue generated from the installation was directly related to the amount of power produced and the price of this power. The price was different if the electricity generated was sold to the electrical grid or used on-site. In this case study both scenarios have been evaluated to analyze whether the use of the electricity generated directly on site rather than selling to the grid increases the economic viability of the installation.

The Spanish tariff based on 6-periods has been applied to the BMI irrigation district (BOE 2014). Since the irrigation behaviour of each farmer is different and the installation is an on-demand irrigation network with a greater flexibility, a weighted average value has been used. The energy cost (€/kW h) used was: May (0.0855), June (0.091292), July (0.105888), August (0.0699).

In contrast, the selling price of the energy for this type of installation is not clearly defined in Spain. Pérez-Sánchez et al. (2016) have established a sales price of 0.0842 €/kW h (Castro, 2006), which is very small in comparison with some other countries such as Ireland with a price fixed of 0.85 €/kW h or Germany with rates over 12.5 cents per kW h.

Fig. 7 shows revenues for on-site usage or selling to the grid for each HPP location and for both scenarios. Values show that revenues coming from direct usage for both scenarios (€29225 and €22185) were slightly higher than those coming from selling to the grid (€27560 and

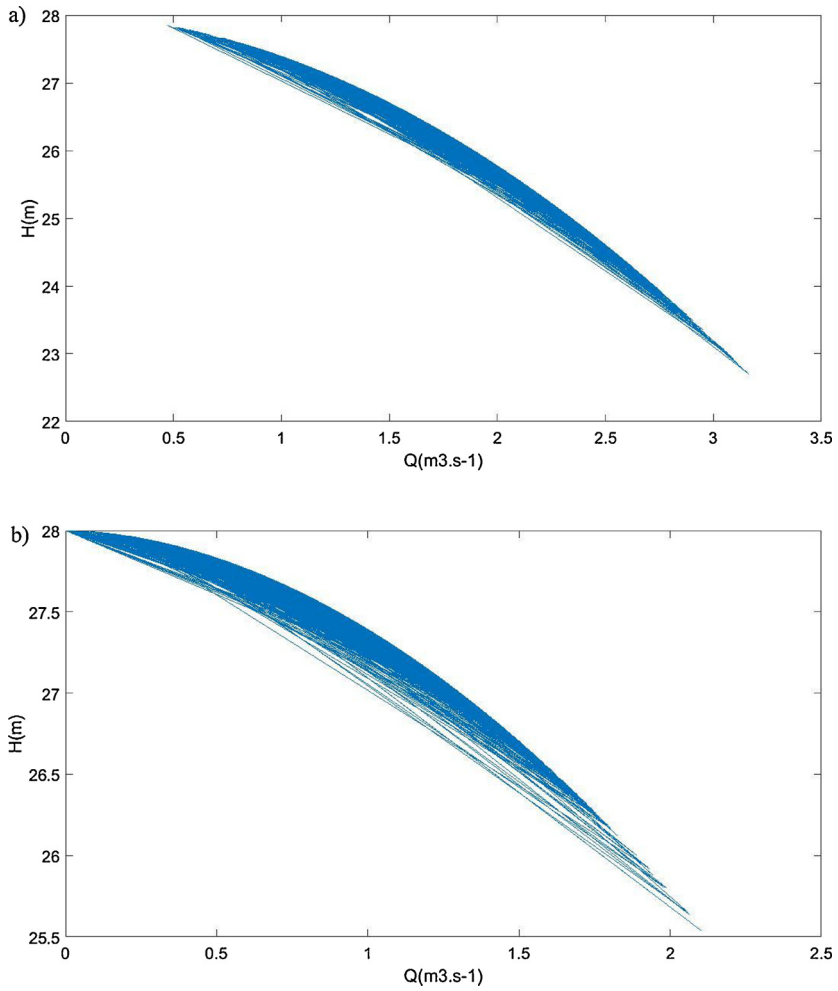

Fig. 5. Flow (m^3/s) versus available head (m) for the Francis turbine in July (a) and April (b).

€20921).

3.4.3. Payback period and energy index

To estimate the payback period a 3% of maintenance and operation cost has been added to the total cost (Eq. (6)). Considering the total cost for the Francis turbine installation and annual total revenues, the payback periods (PP) were 12.7 years for self-supply and 13.4 years if sold to the grid for Scenario 1. These values were 14.4 and 15.2 years for Scenario 2. The total cost per kW or Power Index has been estimated as 1418 and 1607 €/kW for both scenarios and total cost per kW h or Energy Index were 1.37 and 1.55 €/kW h respectively.

The PATs installation payback period for on-site usage was 4.9 years for both scenarios. The payback period increased to 5.2 if the energy were sold to the grid. The power index was 546.7 €/kW and the energy index 0.53 €/kW. These payback periods match with previous estimations in other non-irrigation settings, between 2.5–6 years (Marchis et al., 2014; Lydon et al., 2017a).

4. Discussion

The values of the simulations allow us to make an analysis of the probability of exceedance of a certain flow. This information is critical for the design of the turbine and it is shown in the flow duration curves. The design flow (Q_d) should have a high probability of exceedance, meaning that turbines will work with high efficiencies for the longest period of time. These probabilities were based on the variables influencing flow in the network such as cropping pattern, meteorological conditions, on-farm irrigation efficiency or farmeŕs behaviour, etc.

The aim of examining two scenarios considering the probability of flow exceedance was to highlight the importance of the design flow conditions relative to the actual flow in the network. An optimization problem exists here to find the optimal design flow/head values for the turbine that maximizes the energy recovered or the payback period of the installation. The optimal design conditions and the optimization process should be addressed by future research, once it is demonstrated here that potential for energy recovery exists.

Although the computer simulations and the flow duration curves facilitate an optimal design flow rate, the irrigation network has important flow fluctuation during the irrigation season. Under these circumstances, the PAT/turbine must be installed with a bypass system. The bypass facilitates that the PAT/turbine works near to the BEP, diverting the excess of flow above or below a certain limit of the design flow rate (Q_d). The by-pass system was described in the methodology and enables the turbine to operate with the maximum efficiency during the maximum period of time. This hydraulic regulation is critical not only to achieve high efficiencies values for power generation, but also to control the backpressure and to avoid undesirable phenomena such as cavitation.

As can be seen in Fig. 4 and Table 1, the average flow in May, June, July and August was higher than the design flow rate (Q_d) for both scenarios in all the PATs and the turbine. During these months the delivery of a flow rate higher than Q_d to the PAT/turbine system could result in more energy recovery. However, these installations also must regulate the backpressure. If the flow rate moves away from the BEP the pressure downstream the installation would be compromised. On the other hand, the average flows in April and September are considerably

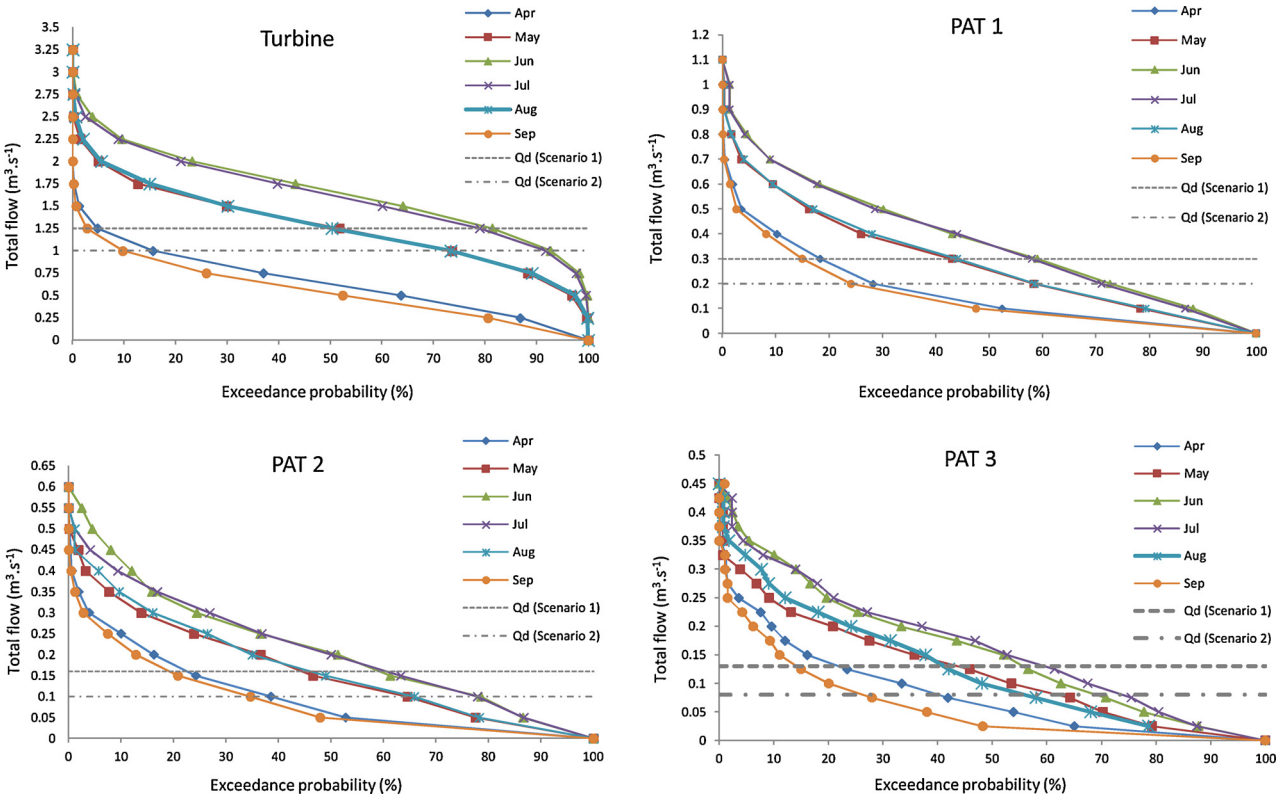

Fig. 6. Flow duration curve per month and per irrigation season (Apr–Sep) for the turbine and PATs.

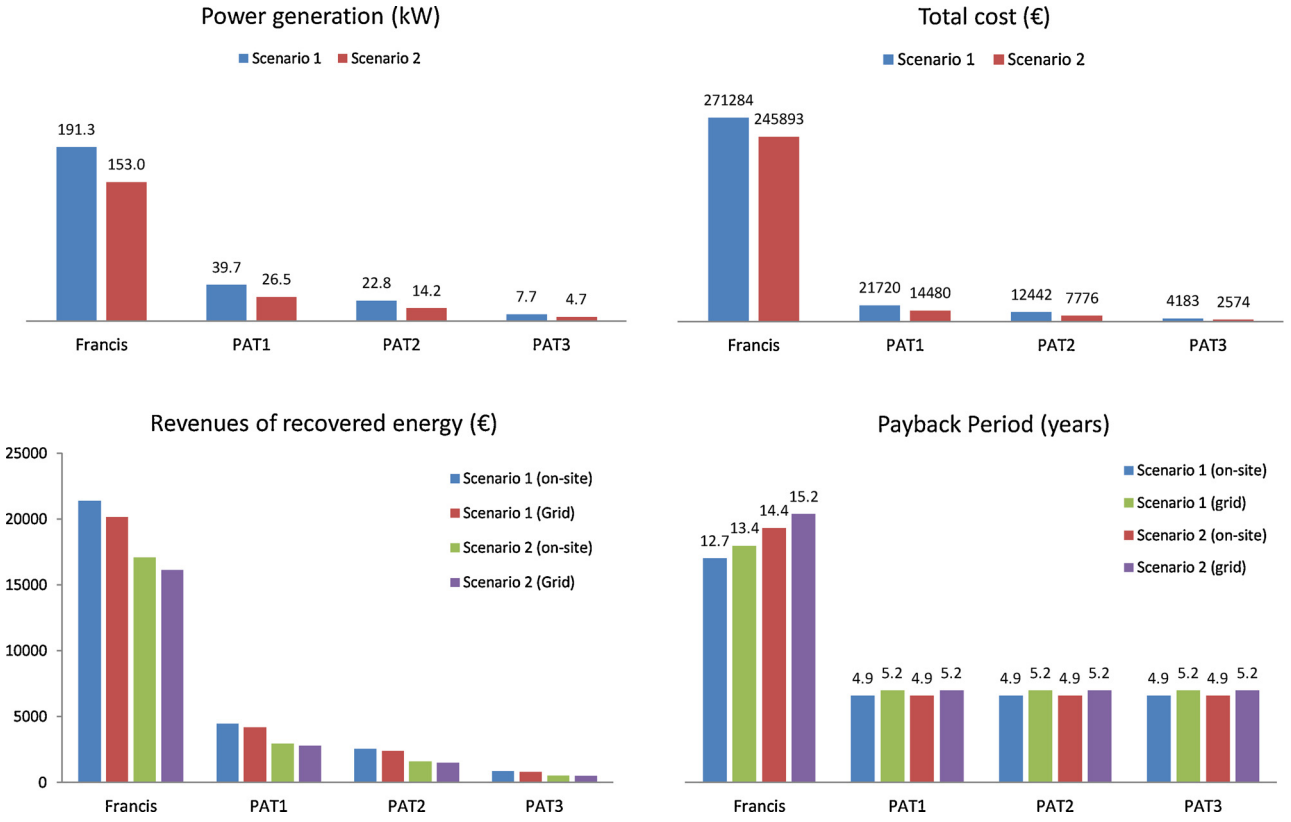

Fig. 7. Potential for Power generation (kW), Energy recovery (MW h), revenues of recovered energy (€) and payback period (years) for both scenarios.

Table 1
Economic feasibility: Payback period and Energy Index.

Electro-mechanical equipment	Flow design Scenario	Flow (m^3/s)	Excess pressure (m)	HPPs Global Efficiency (%)	HPPs Power generation (kW)	HPPs [a]Total Cost (€)	[b]Payback period (on-site) (years)	[b]Payback period (sell to grid) (years)	Power Index (€/kW)	Energy Index (€/kW h)
Francis Turbine (HPP_0)	Scenario 1	1.25	26	0.6	191.3	263382.6	12.7	13.4	1418.1	1.37
	Scenario 2	1.00	26	0.6	153.0	238731.5	14.4	15.2	1606.7	1.55
PAT 1 (HPP_1)	Scenario1	0.30	27	0.5	39.7	21087.7	4.9	5.2	546.7	0.53
	Scenario 2	0.20	27	0.5	26.5	14058.5	4.9	5.2	546.7	0.53
PAT 2 (HPP_2)	Scenario 1	0.16	29	0.5	22.8	12079.9	4.9	5.2	546.7	0.53
	Scenario 2	0.1	29	0.5	14.2	7550.0	4.9	5.2	546.7	0.53
PAT 3 (HPP_3)	Scenario 1	0.13	12	0.5	7.7	4061.3	4.9	5.2	546.7	0.53
	Scenario 2	0.08	12	0.5	4.7	2499.3	4.9	5.2	546.7	0.53
TOTAL	Scenario 1	–	–	–	261.4	300611.5	10.6	11.2	1184.5	1.1
	Scenario 2	–	–	–	198.5	262839.2	12.2	12.9	1363.8	1.3

[a] Total cost including electro-mechanical equipment (65%), piping-fittings-valves (10%) and civil works-manhole-base (25%) (Lydon, 2016).
[b] Payback period estimated as total cost plus 3% of maintenance and operation cost divided by revenues of recovered energy to use on-site or sell to grid.

lower than $Q_{d,}$ implying very low efficiencies, and therefore have not been considered for power generation. Then, only during four months (from May to August) the PAT/turbines can generate energy.

Under these premises, PATs installation were viable for both scenarios since the PP is less than six years (4.9 and 5.2 years respectively) and the EI smaller than 0.6 €/kW h (0.53 €/kW h for both scenarios). According to these values, the Francis turbine installation is not viable economically with PP above 12 years and IE higher than 1.3 €/kW h for both scenarios. However, the payback period of the turbine can be reduced by two years if the total installation of the four turbines is considered (Francis plus the three PATs).

Besides the economic viability, the environmental aspects should be considered. Although the economic feasibility of the Francis turbine is questionable, it could be very valuable from an environmental point of view due to its capability to recover a large amount of energy and therefore reducing CO_2 emissions. The environmental potential of PAT installations has previously been estimated by McNabola et al. (2011), considering that the energy produced by the installations could offset some of the energy demand of drinking water supply. Several authors have used conversion factors to convert kW h of purchased grip electricity to kg of CO_2 emissions to estimate the potential carbon saving in water supply networks (Gallagher et al., 2015; Lydon et al., 2017b). According to the institute for energy diversification and saving in Spain (IDAE, 2014) the conversion factor for conventional electricity in Spain is 0.399 kg eCO_2/kW h. The estimated potential carbon savings of the total installation would result in between 82 and 108.tonnes eCO_2 for both scenarios respectively.

Finally, a PAT/turbine installation plays a leading role in the pressure management of any water distribution network which is a main strategy for leakage reduction. Usually the revenue of recovered water is much larger than the revenue of recovered energy and this could increase the justification of the plant construction, especially in semi-arid regions such as the south of Spain.

Future research should also consider the potential effects of cavitation arising from the installation of turbines in water pipe networks. Limited research has been conducted to date on the effects of cavitation in water pipe networks where turbines are installed for energy recovery purposes.

5. Conclusions

This work shows theoretically that significant energy savings can be achieved by installing traditional turbines or PATs in pressurized irrigation networks. From an economic point of view, traditional turbines do not seem to be viable, with payback periods of over 10 years. On the other hand, PATs have been shown to be very competitive and economically viable, with payback period below 6 years and energy index below 0.6 €/kW h. The energy saving coming from this type of installation could translate into a significant reduction in CO_2 emissions, reducing the carbon footprint of irrigated crops and the agri-food industry. Thus, these technologies represent a potential positive competitive advantage for agricultural production, improving the exploitation cost, reducing the carbon footprint of irrigated crops and increasing the economic feasibility in agricultural production.

Acknowledgment

This research is part of the ESAER project (AGL2017-82927-C3-1-R), funded by the Spanish Ministry of Economy and Competitiveness.

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